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Climate change and the future distribution of palsa mires: ensemble modelling, probabilities and uncertainties

University of Helsinki,
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Contents

List of original publications

This thesis is a summary of research reported in five original articles (Appendices I – V), which are referred to in the text by Roman numerals:

I) Luoto, M., S. Fronzek and F.S. Zuidhoff (2004). Spatial modelling of palsa mires in relation to climate in Northern Europe. *Earth Surface Processes and Landforms*, **29**, 1373–1387.

II) Fronzek, S., M. Luoto and T.R. Carter (2006). Potential effect of climate change on the distribution of palsa mires in subarctic Fennoscandia. *Climate Research*, **32**(1), 1–12.

III) Fronzek, S. and T.R. Carter (2007). Assessing uncertainties in climate change impacts on resource potential for Europe based on projections from RCMs and GCMs. *Climatic Change*, **81**(Suppl. 1), 357–371.

IV) Fronzek, S., T.R. Carter, J. Räisänen, L. Ruokalainen and M. Luoto (2010). Applying probabilistic projections of climate change with impact models: a case study for sub-arctic palsa mires in Fennoscandia. *Climatic Change,* **99**(3), 515-534.

V) Fronzek, S., T.R. Carter and M. Luoto (2011). Evaluating uncertainty in modelling the impact of probabilistic climate change on sub-arctic palsa mires. *Natural Hazards and Earth System Sciences* **11**, 2981-2995.

Author's contribution to the publications

Table 1: Main contributions of authors to the original articles of the thesis.

	I	II	III	IV	V
Original idea	ML	SF, ML	TC, SF	TC, SF	SF, TC
Materials	ML, SF	SF, ML	SF	JR, LR, ML	SF, ML
Analyses	ML, SF	SF	SF, TC	SF, TC	SF, TC
Manuscript preparation	ML, SF, FZ	SF, TC, ML	SF, TC	SF, TC	SF, TC

TC: Timothy Carter, SF: Stefan Fronzek, ML: Miska Luoto, JR: Jouni Räisänen, LR: Leena Ruokalainen, FZ: Frida Zuidhoff

Climate change and the future distribution of palsa mires: ensemble modelling, probabilities and uncertainties

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Fronzek, S. 2013. Climate change and the future distribution of palsa mires: ensemble modelling, probabilities and uncertainties. Monographs of the Boreal Environmental Research No. 44. 35 p.

Abstract

Palsas are mounds with a permafrost core covered by peat. They occur in subarctic palsa mires, which are ecologically valuable mire complexes located at the outer margin of the permafrost zone. Palsas are expected to undergo rapid changes under global warming. This study presents an assessment of the potential impacts of climate change on the spatial distribution of palsa mires in northern Fennoscandia during the 21st century. A large ensemble of statistical climate envelope models was developed, each model defining the relationship between palsa occurrences and a set of temperature- and precipitation-based indicators. The models were used to project areas suitable for palsas in the future. The sensitivity of these models to changes in air temperature and precipitation was analysed to construct impact response surfaces. These were used to assess the behaviour of models when extrapolated into changed climate conditions, so that new criteria, in addition to conventional model evaluation statistics, could be defined for determining model reliability.

A special focus has been on comparing alternative methods of representing future climate, applying these with impact models and quantifying different sources of uncertainty in the assessment. Climate change projections were constructed from output of coupled atmosphere-ocean general circulation models as well as finer resolution regional climate models and uncertainties in applying these with impact models were explored. New methods were developed to translate probabilistic climate change projections to probabilistic estimates of impacts on palsas.

In addition to future climate, structural differences in impact models appeared to be a major source of uncertainty. However, using the model judged most reliable according to the new criteria, results indicated that the area with suitable climatic conditions for palsas can be expected to shrink considerably during the 21st century, disappearing entirely for an increase in mean annual air temperature of 4°C relative to the period 1961-1990. The risk of this occurring by the end of the 21st century was quantified to be between 43% (for the B1 low emissions scenario) and 100% (for the A2 high emissions scenario). The projected changes in areas suitable for palsas are expected to have a significant influence on the biodiversity of subarctic mires and are likely to affect the regional carbon budget.

Keywords: climate change, climate envelope modelling, ensembles, Fennoscandia, impact model, impact response surface, palsa mire, permafrost, probabilistic projection, scenario, uncertainty.

Ilmastonmuutos ja palsasoiden levinneisyys tulevaisuudessa: parviennustaminen, todennäköisyydet ja epävarmuudet

Stefan Fronzek

University of Helsinki, Faculty of Biological and Environmental Sciences, Department of Environmental Sciences, 2013

Fronzek, S. 2013. Climate change and the future distribution of palsa mires: ensemble modelling, probabilities and uncertainties. Monographs of the Boreal Environmental Research No. 44. 35 p.

Tiivistelmä

Palsat ovat turvekumpuja, joiden ydin ei sula kesälläkään. Palsoja esiintyy subarktisilla palsasoilla, jotka ovat ikirouta-alueen reunoilla sijaitsevia ekologisesti arvokkaita suoalueita. Ilmaston lämpenemisen odotetaan aiheuttavan nopeita muutoksia palsasoihin. Tämä tutkimus arvioi ilmastonmuutoksen mahdollisia vaikutuksia palsojen esiintymisalueeseen Fennoskandian pohjoisosassa 2000-luvulla. Tutkimuksessa kehitettiin tilastollisia bioklimaattisia levinneisyysmalleja, joilla ennustettiin tulevaisuudessa palsoille soveltuvia alueita. Palsojen esiintyminen johdetaan malleissa indikaattoreista, jotka perustuvat lämpötilaan ja sademäärään. Analysoimalla bioklimaattisten levinneisyysmallien herkkyyttä lämpötilan ja sademäärän muutoksiin muodostettiin vaikutusvastepintoja. Näitä käytettiin mallien toimivuuden arvioimiseksi, kun mallit ekstrapoloitiin koskemaan muuttuneita ilmasto-olosuhteita. Vaikutusvastepintojen avulla pystyttiin määrittelemään uusia kriteereitä mallien luotettavuuden arvioimiseksi perinteisten arviointimenetelmien lisäksi.

Tutkimus tarkasteli erityisesti vaihtoehtoisia tapoja luonnehtia tulevaisuuden ilmastoa, vaihtoehtojen käyttämistä vaikutusmalleissa sekä tapoja kvantifioida epävarmuutta vaikutusennusteissa. Ilmastonmuutosennusteet laadittiin globaalien ja alueellisten ilmastomallien perusteella ja tarkasteltiin niistä vaikutusmalleihin juontuvia epävarmuuksia. Tutkimuksessa kehitettiin uusia menetelmiä kytkeä vaikutusvastepinnat ilmastonmuutoksen todennäköisyysennusteisiin ja johtaa näin todennäköisyysennusteita ilmastonmuutoksen vaikutuksesta palsoihin.

Tulevaisuuden ilmastoennusteisiin liittyvän epävarmuuden lisäksi vaikutusmallien rakenteelliset erot vaikuttivat olevan suuri epävarmuuden aiheuttaja ennusteissa. Kun käytettiin uusien kriteerien perusteella luotettavimmaksi arvioitua mallia, palsasoiden leviämisalueen ennustettiin kutistuvan huomattavasti 2000-luvulla ja häviävän kokonaan, jos lämpötila nousee yli 4°C verrattuna jaksoon 1961-1990. Riskiksi, että näin tapahtuu ennen vuotta 2100, arvioitiin 43% matalien päästöjen emissioskenaariolla B1 ja 100% korkeiden päästöjen emissioskenaariolla A2. Ennustetut muutokset palsojen esiintymisalueessa vaikuttanevat suuresti subarktisten soiden monimuotoisuuteen ja alueelliseen hiilitaseeseen.

Asiasanat: ilmastonmuutos, bioklimaattinen levinneisyysmalli, parviennustus, Fennoskandia, vaikutusmalli, vaikutusvastepinta, palsasuo, ikirouta, todennäköisyysennuste, skeenario, epävarmuus.

1 Introduction

1.1 Context and motivation

The warming effect of increased greenhouse gas concentrations in the atmosphere has long been discussed. Arrhenius (1896) was the first scientist to estimate the warming effect of increased levels of atmospheric carbon dioxide (CO_2), one of the greenhouse gases, on surface temperatures. Concentrations of CO_2 have increased since industrialization and are now 30 to 40% higher than any values recorded in the past 650 000 years from analysis of air trapped in ice cores (Siegenthaler *et al.* 2005). Other important greenhouse gases such as methane (CH_4) and nitrous oxide (N_2O) have also increased their concentrations as a consequence of human activities (IPCC 2007). At the same time, surface temperatures have increased in many regions of the world during the latter part of the 20th century and have continued to do so until today. The human-induced enhanced greenhouse effect is thought to be the main cause of the global warming trend (IPCC 2007).

Global mean temperatures have increased by 0.6°C during the 20th century (IPCC 2007) and nine of the ten warmest years since the beginning of this period were observed in the decade 2001-2010 (Brohan *et al.* 2006, Jones 2012). The warming has been greatest at higher latitudes, one reason for which are decreases of surface albedo for shorter periods and smaller areas with snow and ice cover in the Arctic that enhance the warming effect (AMAP 2011, Screen *et al.* 2012). Mean annual temperature in the Arctic has increased by 0.9°C during the 20th century (ACIA 2005), while the corresponding value for Finland is 0.7°C, which is still slightly above the global average (Tietäväinen *et al.* 2010). Changes in precipitation, on the other hand, are spatially and temporally more variable, hence only few significant trends have been established, such as increasing winter precipitation in parts of Northern Europe (Bhend and Storch 2008).

Many extreme weather events are directly affected by a shift of the average temperatures. Consequently, the frequency and intensity of high temperature events has increased, while those of low temperature events have generally decreased (IPCC 2007). Examples are the central European heat wave in summer 2003 (Beniston 2004, Schär *et al.* 2004) and that in Russia and eastern Europe in July 2010 (Barriopedro *et al.* 2011), which also strongly affected eastern Finland (Saku *et al.* 2011).

Consequences of the changing climate are manifold and appear across nearly all sectors and in a large variety of human and natural systems. Examples of observed impacts in natural systems from Northern Europe include changes in plant and animal phenology such as an earlier beginning of the growing season of trees (Chmielewski and Rötzer 2002, Linkosalo *et al.* 2009) and other plants (Menzel *et al.* 2006), earlier spring arrival and later autumn departure of breeding birds (Lehikoinen *et al.* 2010), earlier breeding of amphibians and earlier arrival or emergence of butterflies (Parmesan 2007). Some bird and butterfly species have expanded their ranges polewards (e.g. Mitikka *et al.* 2008, Virkkala and Rajasarkka 2010), as have many plant species (Walther *et al.* 2002).

The cryosphere has been affected by changing climatic conditions as documented by shortening ice periods of lakes and rivers in the northern hemisphere (Benson *et al.* 2012), including Finland, a reduction of ice cover in the Arctic Ocean (Stroeve *et al.* 2012) that has started to open up shipping routes between the Atlantic and Pacific Oceans (Shibata *et al.* 2011), shorter snow periods and reduced area and volume of glaciers and permafrost (AMAP 2011) with widespread ecological effects (Post *et al.* 2009).

In the subarctic region of northern Europe, permafrost is not widespread and mainly occurs as mountain permafrost at higher altitudes or in lowlands in palsas (peat mounds with a frozen core – see section 1.3) and peat plateaus (Christiansen *et al.* 2010). Palsas are located in the discontinuous permafrost zone (Callaghan *et al.* 2011). Their marginal location makes them very sensitive even to small fluctuations in climate (Sollid and Sørbel 1998); hence it has been suggested that they could serve as excellent indicators of climate change (Hofgaard

2003). Indeed, local studies suggest that palsas are already in decline, probably due to regional warming (e.g. Zuidhoff and Kolstrup 2000, Luoto and Seppälä 2003). A further loss of this habitat type can be expected for projected future warming, which might have substantial biological implications (Luoto *et al.* 2004) and alter the fluxes of greenhouse gases released from the thawing peat soils (Christensen *et al.* 2004).

Projections of future climate are commonly prepared by applying scenarios of future greenhouse gas and aerosol concentrations as inputs to numerical models that simulate key processes of the climate system (described in more detail in section 1.2). Using a range of these models and scenarios, the Intergovernmental Panel of Climate Change (IPCC 2007) projected an increase in global mean temperature of between 1.1 and 6.4°C by the end of the 21st century relative to 1980-1999.[1] Hence, future warming is expected to exceed, possibly by several times, that observed during the 20th century. Regional and seasonal estimates vary considerably, with larger warming projected for the high northern latitudes, especially during the winter (Christensen *et al.* 2007b). For Finland, the range of warming[2] has been quantified as 2.0-6.5°C by the end of the 21st century relative to 1971-2000, with larger warming in winter (3-9°C) than in summer (1-5°C) (Jylhä *et al.* 2009).

Much work has been conducted in Europe and elsewhere to assess the potential impacts of projected climate change for natural systems and human activities. Numerical models have been developed for this purpose that describe system behaviour under different climate conditions. Examples include impact models for agricultural crops (e.g. Downing *et al.* 2000), water resources (e.g. Veijalainen *et al.* 2010) and natural vegetation (e.g. Hickler *et al.* 2012). Results from studies using such models for European conditions have been summarised in assessment reports (e.g. Alcamo *et al.* 2007, AMAP 2011, EEA 2012).

In impact assessments, uncertainties propagate through a chain of analysis steps, commonly being amplified in each of them (Figure 1). Impacts are typically at the end of this chain and therefore subject to several sources of uncertainty. This has been referred to as the "cascading pyramid of uncertainty" (Schneider 1983) or the "cascade of uncertainty" (e.g. Jones 2000). The chain of analysis starts with uncertainties in the drivers of future emissions, such as population, social structure and technological development, which can greatly affect the global demand for energy, the production of which is a major cause of greenhouse gas emissions. Emissions are next converted into concentrations of different greenhouse gases and aerosols using models of the carbon cycle and atmospheric chemistry. The atmospheric concentrations are interpreted in terms of their radiative effect on the climate system (radiative forcing), which is used to force global climate models. Additional uncertainties are introduced when attempting to regionalize or downscale estimates from global models to a finer scale more relevant for impact analysis, for which several alternative techniques are available. Regional climate scenarios are then used to estimate impacts of climate change, which have their own sources of uncertainties.

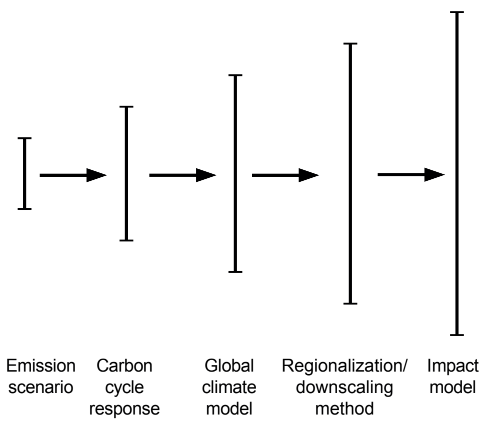

Figure 1. Cascade of uncertainty in climate change impact assessments. Source: adapted from Jones (2000).

[1] This range of projections has been assigned a likelihood of greater than 66% by the IPCC.

[2] The range was expressed as the 5th to 95th percentiles of an ensemble of 19 GCMs for three emission scenarios.

The conventional approach to examine climate change impacts with numerical impact models has been that a limited number of deterministic climate scenarios, selected to embrace as realistic a range of uncertainties as possible, are run through a single impact model. Uncertainties both of climate projections and of impact estimates are commonly only quantified to a limited extent. This is in spite of the ready accessibility of multiple climate model projections from open access data archives (e.g. Christensen *et al.* 2007a, Meehl *et al.* 2007a); however, the handling of these vast and rapidly expanding data resources remains a major challenge, especially for impact analysis with more complex models that require detailed input data.

The number of climate model simulations has increased in parallel with the development of computing power. Larger numbers of simulations can help to quantify the uncertainty of climate projections which can be seen in attempts to estimate probability density functions (PDFs) of future climate changes globally (Murphy *et al.* 2004, Meehl *et al.* 2007b) and for smaller regions (Räisänen and Ruokolainen 2006, Harris *et al.* 2010, Frieler *et al.* 2012). Using such PDFs of climate changes with impact models provides an opportunity to go beyond "what-if" type studies of potential impacts towards quantitative assessments of the likelihood that a certain impact will occur. However, it may also require new approaches for impact analysis to be developed.

1.2 Methods of characterising the future for impact studies

One major objective in model-based climate change impact assessments is the estimation of future impacts. For this, a climate-sensitive impact model is required of which many have been developed describing key aspects in various sectors (see section 1.1 above), ranging from simple empirical-statistical indices to complex processed-based models. Next, a characterisation of the future climate and other aspects of the future are needed. Carter *et al.* (2007) identify several approaches of characterising the future that differ in their comprehensiveness and likelihood (Figure 2).

Artificial experiments, ranging from simple thought-experiments to detailed modelling studies, follow a coherent logic without regard to plausibility. In s*ensitivity analyses*, the values of a reference or baseline case of one or several variables are adjusted. Temporal and spatial *analogues* can be used to represent fu-

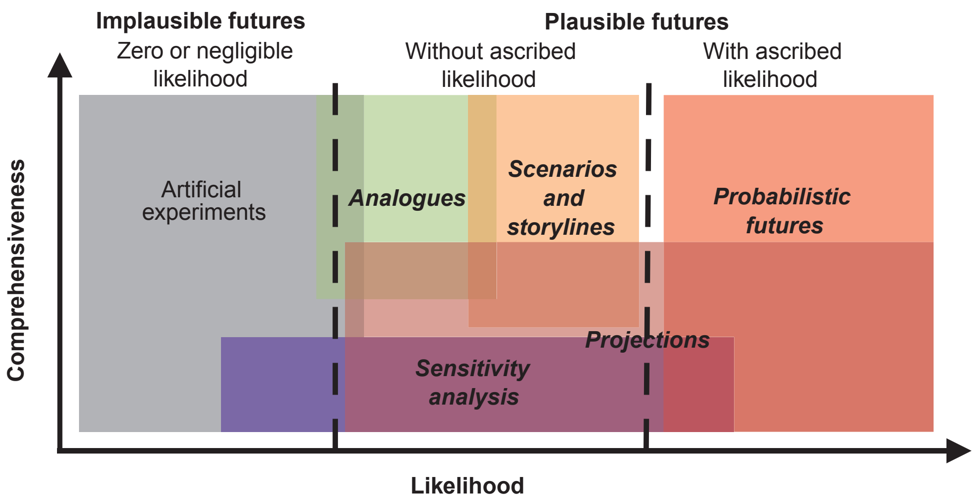

Figure 2. Characterisations of the future. The approaches used in the present-study are marked in italic. Source: adapted from Carter et al. (2007).

ture conditions of a study regions inferred from situations from the past or a different location. *Projections* are sometimes broadly referred to as model-derived quantifications of an aspect of the future; therefore, several approaches of characterising the future can be regarded as a projection. *Scenarios* are "coherent, internally consistent and plausible descriptions of a possible future state of the world" (IPCC 1994, p. 3). They are not forecasts or predictions, but instead each scenario provides an alternative future without assigned likelihoods (Nakićenović *et al.* 2000). *Storylines* are qualitative narratives describing general trends and events. Often, they provide the qualitative basis for quantifications with model-based projections that together form a scenario (Rounsevell and Metzger 2010). *Probabilistic futures* have ascribed likelihoods that quantify some aspects of the uncertainty, sometimes also conditional on the assumptions of a single scenario. Several of the approaches sketched in Figure 2 have been used to characterise future climate in the present study.

A common approach in impact assessments during recent decades has been the use of climate scenarios prepared with climate model simulations that were forced by scenarios of future emissions. One such set of emission scenarios is described and quantified in the Special Report of Emission Scenarios (SRES; Nakićenović *et al.* 2000) that has been the basis for climate model simulations prepared for the third and fourth assessment reports of the IPCC (IPCC 2001, 2007). SRES contains a set of alternative scenarios that make different assumptions about future development in socio-economic variables driving emissions that influence the level of greenhouse gas concentrations in the atmosphere. Four narrative storylines have been developed that describe the world as integrating globally with economic emphasis (labelled the A1 storyline), global but with environmental emphasis (B1), and a development towards regionalisation with economic (A2) or environmental (B2) emphasis. Using integrated assessment models, in total 40 alternative quantifications of future emissions and their effect on atmospheric greenhouse gas concentrations and radiative forcing have been prepared for these storylines, spanning a large range of uncertainty. Six of these were selected as so-called "illustrative marker scenarios" (Nakićenović *et al.* 2000) and have been used to force simulations with climate models.

The most sophisticated tools currently available to simulate the response of the climate system to increased greenhouse gas concentrations are coupled atmosphere-ocean general circulation models (GCMs). These divide the Earth's atmosphere and oceans into a 3-dimensional grid and simulate large-scale processes between the different boxes. Some important processes occurring on smaller, sub-grid scales (e.g. related to the formation of clouds) are represented by a technique known as "parameterisation". This simplification of the climate system accounts for some of the uncertainty in climate modelling.

The horizontal resolution of coupled GCMs typically ranges between 150 and 600 km (Randall *et al.* 2007) and is usually much coarser than that relevant for most impact assessments (Mearns *et al.* 2003). Therefore, GCM output is typically regionalized or downscaled to a finer spatial resolution, using either statistical or dynamic approaches.

The simplest regionalization method is the delta-change approach, in which changes simulated with GCMs are added to observed climate which can be at a finer spatial resolution or for individual sites (Fowler *et al.* 2007). Usually changes in inter-annual or daily variability are not treated (e.g. Fronzek *et al.* 2012). The delta-change method assumes the bias of a climate model simulation for the baseline period to remain constant in the future. More sophisticated statistical downscaling methods include regression models weather classification schemes and weather generators (Wilby *et al.* 2004). These usually involve the development of statistical relationships between large-scale and local observed climate variables, assume these to remain constant over time and apply them to predict the future local climate from future large-scale conditions simulated by a GCM (Carter 2001).

Dynamic downscaling is conducted with Regional Climate Models (RCMs) that simulate the effect of increased greenhouse gas concentrations on climate over a limited spatial domain, but with higher horizontal resolution than GCMs. The conditions at the boundary are usually taken from GCM simulations. RCM experiments conducted for Europe have been conducted for grid sizes between 25 and 50 km cell length in the PRUDENCE (Christensen *et al.* 2007a) and ENSEMBLES (van der Linden and Mitchell 2009) projects. The outcome of an RCM simulation is strongly affected by the boundary conditions of the GCM within which it has been nested (Déqué *et al.* 2007), and, as with the GCM, control simulations show biases compared to observations (Jacob *et al.* 2007). Hence, a correction of model bias is still needed for most impact studies.

1.3 Palsa mires

This climate change impact study focuses on the case of subarctic palsa mires. Palsas are mounds with a permafrost core covered by peat and occur in subarctic mires (palsa mires). Palsas have a height between 0.5 and 10 metres above the mire surface (Åhman 1977, Seppälä 1988) with a diameter ranging between 2 and 150 metres and a minimum thickness of the peat layer of about 0.5 metres (Seppälä 2011). A typical example of a palsa from northern Finland is shown in Figure 3. Their distribution is confined to regions with climatic conditions exhibiting low annual temperature, relatively thin snow cover and a low amount of precipitation (Seppälä 1986). With their distinct morphology, palsas are good indicators of permafrost in otherwise permafrost-free mires (Luoto and Seppälä 2003). The term "palsa" originates from the language of the indigenous Saami people and is used with the same meaning, for example, in English, German, Finnish and French (Aapala and Aapala 2006).

Figure 3. Palsa near Kelottijärvi, Enontekiö, Lapland, Finland, 25 September 1995. Source: image bank of the Environmental Administration, photo credits: Aarno Torvinen.

Palsas naturally go through a dynamic cycle of development from formation to decay even without changes in environmental conditions, as has been described by Seppälä (1986). They start to form in the winter in locations with little snow, for example when wind is locally thinning the snow cover, and the frost can penetrate deep into the soil. Through frost heaving triggered by ice lenses, the mire surface rises and develops into what Seppälä termed a "palsa embryo", which dries out during the summer. Due to the low thermal conductivity of dry peat, the peat cover provides an effective insulation that can allow the frozen core to survive during even relatively warm summers (Kujala *et al.* 2008). Wet or frozen peat, on the other hand, has a much higher thermal conductivity. After autumn rains, this allows the frost in the next winter to penetrate deeply into the soil, causing the palsa surface to rise further. This process is repeated until the palsa reaches a mature stage. Cracks at the palsa surface can now start to develop which initiates a collapse stage, with erosion of peat blocks along the cracks (Zuidhoff 2003). The insulating effect of the peat on the collapsing palsa is reduced, leading to the thawing of permafrost and development of thermokarst ponds formed by the meltwater (Luoto and Seppälä 2003). Under suitable climatic conditions, this unique cycle of palsa development is repeated. Palsa mires therefore often contain palsas at different development stages, creating a very heterogeneous landscape that is characterised by the dry palsa hummocks and wet thermokarst ponds. It has been argued that this unique successional behaviour and cycle of development of palsa mires marks them as exceptional geomorphological formations in subarctic landscapes that are worth conserving in their own right (Luoto *et al.* 2004).

Palsa mires have been found throughout the subarctic of the northern hemisphere in locations where a sufficiently thick peat layer exists and suitable climatic conditions are present (see Figure 4). Palsa locations were reported from Fennoscandia (Sollid and Sørbel 1998, Luoto *et al.* 2004), Iceland (Thórhallsdóttir 1994, Kneisel *et al.* 2007), Svalbard (Åkerman 1982), Russia (Åkerman 1982, Oksanen *et al.* 2003, Jankovskà *et al.* 2006, Barcan 2010, Kirpotin

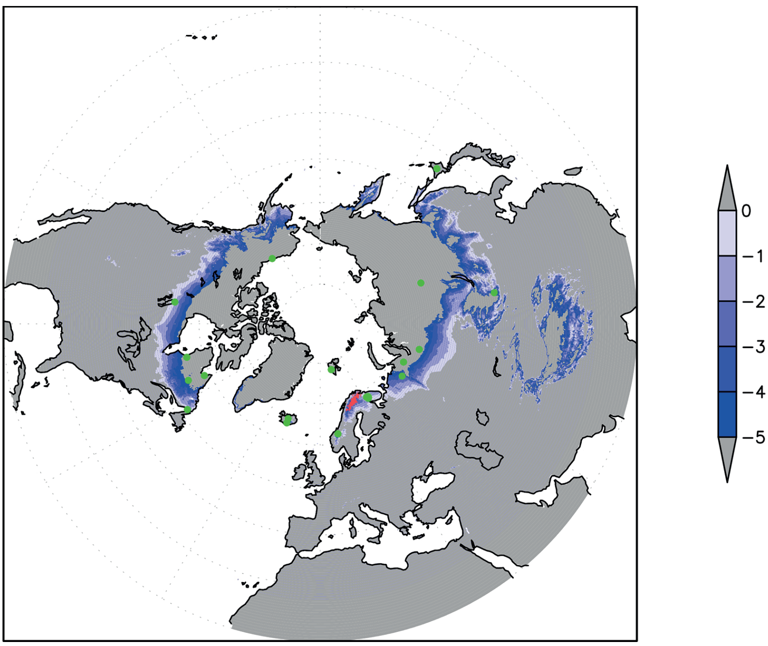

Figure 4: Palsa occurrences reported in the literature (green points), the northern Fennoscandian distribution from Luoto et al. (2004) (red area) and the mean annual temperature between -5 and 0°C (blue shading) for the period 1961-1990 from the CRU CL 2.0 gridded temperature data set (New et al. 2002).

et al. 2011), Mongolia (Sykles and Vanchig 2007), Japan (Sone 2002), Alaska (Tsuyuzaki *et al.* 2007) and Canada (Thie 1974, Dionne 1984, Doolittle *et al.* 1992, An and Allard 1995, Payette *et al.* 2004), although it is not always clear if these reports are based on a common definition of a palsa whose permafrost has developed in peat[3]. Relicts of possible former palsas have also been reported from the southern hemisphere in Argentina (Trombotto 2002). The northern limit of the distribution is usually defined by continuous permafrost. In many places, the palsa distribution demarcates the southern limit of the discontinuous permafrost zone. This marginal location makes palsas very sensitive to even small fluctuations in climate (Sollid and Sørbel 1998). In fact, palsas are in decline throughout their distribution as has been observed in Fennoscandia (Matthews *et al.* 1997, Zuidhoff and Kolstrup 2000, Luoto and Seppälä 2003, Åkerman and Johansson 2008), Russia (Kirpotin *et al.* 2011) and north America (Beilman *et al.* 2001, Payette *et al.* 2004, Camill 2005, Vallée and Payette 2007) and this decline has been linked with increases in regional air temperature.

The heterogeneous environments of palsa mires offer distinct ecosystem services that are characterised by a rich species diversity (CAFF 2001). Palsas are preferred breeding grounds for bird species and offer resting places for migrating birds (Järvinen and Väisänen 1976, Järvinen 1979). Furthermore, the European distribution of the dragonfly *S. sahlbergi* is believed to be totally restricted to palsa mires (Schröter 2011). Consequently, the value of palsa mires for nature conservation has been recognised and they have been listed as one of 65 priority natural habitat types in Annex I of the "Habitats" Directive of the European Union (Anon. 2007).

Permafrost stores significant amounts of carbon that, if the permafrost thaws as a result of warming, potentially can be released to the atmosphere and thus provide a feedback to the climate system (Schuur *et al.* 2008). Thawing and disintegration of permafrost formations in palsa mires modifies hydrology and vegetation dynamics. In Fennoscandia, this has resulted in wetter hydrological conditions with a greater proportion of thermokarst ponds (Luoto and Seppälä 2003, Christensen *et al.* 2004). On a landscape-scale, these transitions have been observed to lead to increases in CH_4 emissions to the atmosphere (Christensen *et al.* 2004), but to decreases or even an uptake of CO_2 (Bäckstrand *et al.* 2010) through a shift from dry hummock to moist hummock vegetation with a higher carbon fixation (Bosiö *et al.* 2012). The balance of these two counteracting effects depends on local hydrological conditions and vegetation structure. Bosiö *et al.* (2012) scaled flux measurements from individual palsa sites to estimate a regional carbon budget of northern Fennoscandian palsa mires; their results indicated that the effect of carbon fixation by plants may be larger than that of increases in CH_4 emissions for their study region by the mid-21st century, although large uncertainties in this estimate were acknowledged.

1.4 Objectives of this study

The main thesis of this work is that conventional approaches to examine potential climate change impacts often fall short in rigorously representing uncertainties both in the future climate and in its impacts. This work attempts to demonstrate how limited and potentially misleading conventional methods can be, by comparing them with more comprehensive methods tailored to the problem in hand.

The subarctic palsa mires of northern Fennoscandia serve as a case study, for which several contributors to the "cascade of uncertainty" in assessing impacts of future climate change are addressed. The study has three main components, which are first, an examination of present-day palsa distribution and its relation to climate, second, projections of future climate and third, modelling the impact of climate change on the palsa distribution both using conven-

[3] The literature is not consistent in the use of the term palsa. Some authors, including Seppälä (1986), define palsas as peat-covered mounds with a frozen core, whereas others also use the term palsa for mounds in mineral soil without any peat, which are alternatively referred to as *lithalsas* (Pissart 2002).

tional scenarios analysis and in a probabilistic framework. In each of these elements, special attention is paid to the treatment of uncertainties (Figure 5).

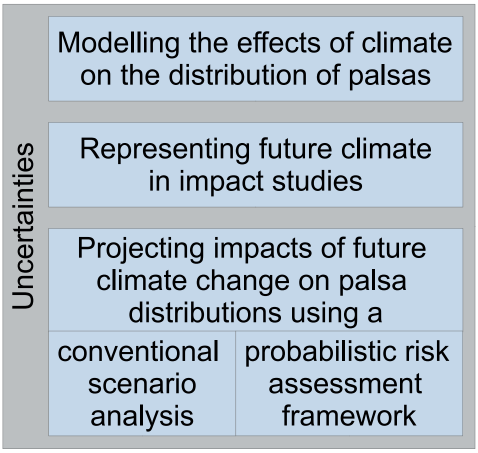

Figure 5: Components of the thesis.

Specifically, the thesis has the following objectives, grouped by its components:

Modelling the effects of climate on the distribution of palsas and associated uncertainties

1. To assess to what extend the spatial distribution of palsa mires can be explained by climate on a regional scale, and construct statistical models of this relationship;
2. To apply the statistical models to investigate the sensitivity of the palsa distribution to changes in climate;
3. To evaluate the robustness and plausibility of model extrapolations and to quantify the uncertainties of climate envelope models for palsa mires.

Representing future climate in impact studies

4. To investigate the added value of climate change projections dynamically downscaled with regional climate models (RCMs) compared to projections of general circulation models (GCMs) in model-based impact assessments;
5. To develop methods of applying probabilistic climate projections with impact models.

Projecting impacts of future climate change on palsa distributions

6. To project changes in the palsa mire distribution during the 21st century;
7. To define a critical climate change for northern Fennoscandia that would induce the total disappearance of palsa mires, and estimate the risk and timing of such an occurrence.

2 Materials and methods

2.1 Study area

The study area is located in northern Fennoscandia and covers the boreal forest and tundra regions of subarctic Norway, Sweden and Finland. The southern border is defined by the Polar Circle (66°33’N). The Norwegian coastline borders the study area to the west and north, the eastern border is defined by the border with Russia. The area has been divided into 1913 land cells with a regular spacing of 10’ x 10’ spatial resolution (18.5 km x 6.7 km = 123.3 km^2 at 69°N) and covers in total ca. 240 000 km^2 (see Fig. 1 in paper **I**). The altitude ranges from sea level on the Norwegian coast to Sweden’s highest peak, Kebnekaise, at 2214 m a.s.l. The climate varies widely in the study area from maritime on the Norwegian coast towards more continental in Finland. Annual precipitation totals range from 370 mm in northern Sweden to 2170 mm at the coast. The coastal areas also have the highest mean annual temperature of +4.7°C, while the lowest temperature in the study area, -6.0°C, is found in the mountains of northern Sweden.

In addition to the palsa studies for Fennoscandia, a broader-scale analysis of climate indicators for Europe is also presented, based on a regular grid with a spatial resolution of 0.5° x 0.5° over a European window stretching from 35° to 75°N latitude and 15°W to 35°E longitude. This domain is displayed, for example, in Fig. 2 of paper **III**.

2.2 Palsa mire distribution data

The spatial distribution of palsa mires in the study area was recorded on the same regular 10' x 10' grid for which climate data were also available (see below). The presence or absence of palsa mires was recorded for each grid cell and stored in a geographical information system. The information was collected from a variety of different sources including journal articles, published books, geomorphological and geological maps published between 1962 and 2002 (see paper **I** for references).

2.3 Observed climate data and climate projections for the 21st century

Baseline climate data comprised observed monthly mean temperature and precipitation interpolated to a regular grid over Europe. These were obtained from the University of East Anglia's Climatic Research Unit (CRU) at two spatial resolutions, 10' x 10' (CRU_TS_1.2, Mitchell *et al.* 2004) extracted for the period 1951-2000 and 0.5° x 0.5° (CRU_TS_2.0) extracted for the period 1961-1990 (Mitchell and Jones 2005). These gridded datasets have been constructed from meteorological observations by first interpolating monthly long-term averages for the period 1961-1990 as a function of latitude, longitude, and elevation using thin-plate splines (New *et al.* 1999). The station network for this was relatively dense over the northern Fennoscandia study region. A time-series of monthly anomalies interpolated using angular distance-weighted interpolation was then added to the long-term average (Mitchell and Jones 2005). The station density of the time-series data was smaller in many areas including northern Fennoscandia and varied over time. The anomaly approach allowed to incorporate the greater spatial detail provided with the interpolation for the long-term average also for time steps for which fewer station data were available. For the analysis of this study, 30-year monthly means were calculated for the periods 1951-1980, 1961-1990 and 1971-2000 and time-series data were used for the period 1961-1990 (Table 2).

Climate projections for the 21st century were constructed using the delta-change approach (see section 1.2) with several ensembles of GCM and RCM simulations and two probabilistic datasets covering a range of emission scenarios (Table 2). Monthly changes between long-term averages of future periods and the baseline period, 1961-1990, were calculated for temperature and precipitation. The changes were then added (or multiplied in case of relative changes) to the observed climatology of the baseline period. Ensembles of GCM simulations were taken from archives prepared for the IPCC Third Assessment Report (TAR, IPCC 2001) and the Coupled Model Intercomparison Project Phase 3 (CMIP3, Meehl *et al.* 2007a) for SRES emission scenarios, as well as from the ENSEMBLE project for an emission scenario (E1) with strong mitigation measures (Johns *et al.* 2011). An ensemble of RCM simulations was taken from the PRUDENCE project (Christensen *et al.* 2007a). Temperature data from each year of the RCM simulations and the driving GCM were also used to analyse the changes in the inter-annual variability.

To allow a probabilistic assessment, the sample size of one of the GCM ensembles was increased using a re-sampling method developed by Räisänen and Ruokalainen (2006). A second probabilistic dataset, labelled the "Grand Ensemble", was provided by Harris et al. (2010) who combined the results of a perturbed-physics experiment of a single GCM with a multi-model ensemble to quantify the uncertainty of regional climate change projections. In these two probabilistic datasets, changes in temperature and precipitation are described by joint frequency distributions with sample sizes of several hundred for the re-sampling method, and 10000 for the Grand Ensemble.

Table 2: Datasets of observed and projected climate used in the thesis and the papers in which they were employed.

Data set	Reference	Emission scenarios	Time periods	Paper
Observed gridded climate data				
CRU_TS_1.2 (0.5° x 0.5°)	Mitchell & Jones (2005)		1961-1990 climatology and interannual variability	**III**
CRU_TS_2.0 (10' x 10')	Mitchell et al. (2004)		1951-1980, 1961-1990 and 1971-2000 climatologies	**I, II, IV,V**
Future projections				
7 GCMs (IPCC-TAR)	IPCC (2001)	SRES B2, A2, B1*, A1FI*	Three 30-year period-averages (2010-39, 2040-69, 2070-99/2071-2100)	**II, III**
9 RCMs and their driving GCMs (PRUDENCE)	Christensen et al. (2007)	SRES B2, A2	30-year period-averages (2071-2100) and interannual variability	**III**
7 GCMs forced with the E1 mitigation scenario (ENSEMBLES)	Johns et al. (2011)	E1, SRES A1B	Two 20-year period-averages (2010-2039, 2070-2099)	**V**
Probabilistic projections from re-sampled 21-GCM ensemble (CMIP3)	Räisänen & Ruokolainen (2006)	SRES B1, A1B, A2	Nine 30-year period averages (1991-2020, … 2071-2100)	**IV**
Probabilistic projections "Grand Ensemble", perturbed-physics experiment and multi-model ensembles (ENSEMBLES)	Harris et al. (2010)	SRES A1B	Nine 20-year period averages (2000-2019, 2010-2029, 2020-39, …, 2080-2099)	**V**

*GCM simulations for these emission scenarios were not directly available, but instead outputs from different forcing scenarios were pattern-scaled to represent regional climate changes under the SRES A1FI and B1 emission scenarios (Ruosteenoja et al. 2007).

2.4 Climatic indices

A number of indices were calculated with observed and scenario climate data to describe climatic conditions in northern Europe relevant for palsas and other ecosystems or human activities:

- Annual, summer (May-September) and winter (October-April) precipitation totals.
- Mean annual air temperature.
- A continentality index defined as difference between the maximum and minimum values of mean monthly temperatures.
- Effective temperature sum (ETS) that accumulates daily mean temperatures above or below a threshold temperature. Different thresholds were used to define freezing (FDD), thawing (TDD), growing (GDD) and cooling (CDD) degree-days. Two alternative methods were used to estimate ETS from monthly mean temperatures, 1) in paper **I** by first interpolating monthly values to daily using a sine-curve interpolation method (Brooks 1943), and 2) in papers **II**, **III**, **IV**, and **V** by integrating the ETS function over an assumed Gaussian daily temperature distribution (Kauppi and Posch 1985). Thresholds for GDD were also applied to define the thermal suitability of crops.
- Frost number defined as a function of FDD and TDD (see paper **I**).
- Length of the thawing and thermal growing periods defined as the periods when mean daily temperature is above 0°C and 5°C, respectively.
- An index of potential biomass defined according to an empirical relationship between measurements and long-term mean annual temperature and precipitation (Lieth 1975). This model does not directly account for the fertilizing effect of increased CO_2 concentrations.

While some of these indices were used to analyse the climatic envelope of the northern Fennoscandian palsa distribution (see next section and papers **I**, **II**, **IV**, **V**), paper **III** explored indicators that are also relevant for other impact sectors to study uncertainties in downscaling methods and the effect of changes in inter-annual variability.

2.5 Modelling the spatial distribution of palsa mires

The spatial distribution of northern Fennoscandian palsa mires was studied by means of climate envelope models. Envelope modelling techniques involve attempting to correlate the spatial distribution of species or habitats to environmental predictor variables (Guisan and Zimmermann 2000). More recently, such techniques have also been applied with distribution data of geomorphological processes and landforms (Luoto and Hjort 2004, Hjort *et al.* 2007, Hjort and Luoto 2013). Using climate variables as predictors, envelope models can be used to assess the effect of changes in climate on the spatial distribution of the response variable (Heikkinen *et al.* 2006). The basic assumption here is that the spatial distribution is in equilibrium with the current climate.

Eight envelope modelling techniques were used in this study to relate palsa presence/absence with climate: Generalized Linear Modelling (GLM), Generalized Additive Modelling (GAM), Classification Tree Analysis (CTA), Artificial Neural Networks (ANN), Multiple Adaptive Regression Splines (MARS), Mixture Discriminant Analysis (MDA), Random Forests (RF) and Generalized Boosting methods (GBM); these are described briefly in papers **II** and **V** (and see Table 1, paper **V**). They differ in their conceptional approaches and concrete algorithms and can be grouped into regression (GLM, GAM, MARS), classification (CTA, MDA) and machine-learning methods (ANN, RF, GBM) (Marmion *et al.* 2008). The application of several techniques facilitated the quantification of uncertainties attributable to differing model structure.

Models were calibrated in a split-sampling approach that randomly divides the data into separate subsets for model calibration and for evaluation. Two evaluation statistics were calculated, the area under the receiver operating characteristics curve (AUC) and the Kappa coefficient of agreement. AUC is a threshold-independent method to evaluate model predictions (Guisan and Zimmermann 2000); the Kappa coefficient is a measure of correct predictions adjusted for agreement that might occur by chance (Heikkinen *et al.* 2006).

The calibration and evaluation of climate envelope models for palsa mires was conducted in three steps to distinguish several sources of impact model uncertainty. First, the relationship of the palsa mire distribution to a larger set of climatic predictor variables and their relative significance was tested with a single modelling technique (paper **I**). Uncertainty of structural model differences was then studied by comparing a larger set of five modelling techniques calibrated with the most significant predictor variables (paper **II**). Finally, the parameter uncertainty of each of these five and three additional modelling techniques was quantified and combined with an estimate of uncertainty in initial conditions, sampled using different baseline periods (paper **V**). A total of 600 palsa models was analysed in the last step to quantify the most important sources of uncertainty more fully.

The palsa models were applied with deterministic climate scenarios for time periods of throughout the 21st century in a conventional impact assessment to project the future distribution of palsa mires (paper **II**).

2.6 Impact response surfaces and probabilistic assessment

The sensitivity of the palsa models to systematic changes in climate variables was tested and used to construct two-dimensional impact response surfaces. These show changes in the area suitable for palsas in relation to changes in mean annual temperature and precipitation. Since the predictor variables of the palsa models require monthly mean temperature, four alternative scaling functions were applied that made different assumptions for converting mean annual temperature changes to monthly changes (paper **IV**). These different versions of the impact response surface were then overlaid with probabilistic projections of climate change that are defined on the same axes as joint frequency distributions of temperature and precipitation changes. The change in area suitable for palsas was evaluated from the impact response surface for the combination of changes in temperature and precipitation of each member of the probabilistic climate change sample. This defined a sample of estimates of changes in suitable palsa area with the same sample size as the climate change projections. Two thresholds for the palsa distribution were defined, the reduction of suitable area to less than half of the baseline palsa distribution and the total loss of area suitable for palsas. The latter represents a critical threshold for the presence of palsa mire habitats in the study region, whereas the first threshold was arbitrarily selected to quantify intermediate impacts. The risk of exceeding these thresholds was then calculated from the sample of impact estimates. Additional impact estimates were calculated by evaluating impact response surfaces for temperature and precipitation changes projected for the E1 mitigation scenario.

In paper **IV**, an analysis with different versions of impact response surfaces for a single palsa envelope model was conducted and compared to the conventional assessment where model simulations were conducted for all members of the probabilistic climate change ensemble. In paper **V**, impact response surfaces were constructed for the full ensemble of 600 palsa models and evaluated with probabilistic projections of climate change.

3 Results

3.1 Present-day distribution of sub-arctic palsa mires and its climatic factors

The observed palsa distribution map constructed for paper **I** indicates that 28.5% of the 1913 grid cells contained palsa mires (Figure 1 in paper **I**). Averages of climatic variables in these grid cells showed clear differences compared to climate in grid cells without palsa mires, with a lower mean annual temperature, lower annual precipitation, a higher number of freezing degree-days and a higher frost number. Climatological thresholds and optima were determined by fitting logistic regression models to individual climate variables in turn. This revealed an optimal range of (long-term) mean annual temperature for northern Fennoscandian palsa mires of between -4.99°C and -2.87°C. The upper threshold, defined with a less than 5% probability of palsa presence for temperature above this threshold, was at -0.33°C. The optimum annual precipitation was less than 445 mm and the threshold value of 720 mm. Thresholds and optima were also determined for other climate variables (Table V and Figure 3 in paper **I**).

Multivariate climate envelope models had an excellent fit[4] in terms of evaluation statistics (Table IV in paper **I**, Table 3 in paper **II**, Table 3 in paper **V**) and were able to reproduce the observed distribution of palsa mires (*cf.* Figure 2E in paper **I** and Figure 3 in paper **II**).

3.2 Projections of future climate and its representations

Climate change projections for northern Europe employed in this study showed consistent warming that is strongest in winter and increases in annual precipitation throughout the 21st century (Figure 1 in paper **III**, Figure 3 and 4 in paper **IV** and Figure 3 in paper **V**). The projected changes by 2071-2100 relative to 1961-1990 result in changes of climatic indices relevant

[4] Evaluation statistics were evaluated with approximate accuracy guides for AUC (Swets 1988) and kappa (Monserud & Leemans 1992).

for many sectors and are also characterised by a poleward shift of climatic zones. The northern limits of areas suitable for the cultivation of soya bean and grain maize were estimated to shift between several hundred and 2000 kilometres northwards (paper **III**; see also Olesen *et al.* 2007), the thermal growing season in northern Europe to lengthen by three to twelve weeks (Figure 4 in paper **III**) and a simple index of net primary productivity to increase by up to 50% in northern Europe (Figure 6).

In order to evaluate the effect of climate model bias (see section 1.2) on estimates of impacts, some climatic indices were calculated for the baseline period using RCM output directly. These indicated substantial differences from the results of calculating the indices with observed climate data, though were smaller for indices based only on temperature (Figure 6 in paper **III**) than for the index of net primary productivity that requires both temperature and precipitation. It also provided strong arguments for applying the delta change method in subsequent analyses. Results for impact indices using RCM-based climate projections showed a close resemblance to those obtained from projections of their bounding GCM. Hence, the range of uncertainty obtained from the ensemble of RCMs did not embrace the full range of future impacts of an ensemble of GCMs that, in principle, could have been used for downscaling (Figure 2 and 4 in paper **III**). The range of impact estimates was largest when analysing an ensemble of GCMs with four different emission scenarios. This resulted in a range of estimates of suitability expansion for grain maize cultivation of more than 2000 km, while the comparable range for an ensemble of 6 GCMs (assuming only A2 emissions) was less than 700 km (Figure 2 in paper **III**). The lengthening of the thermal growing season was estimated to be between 3 to 12 weeks for the GCM ensemble with four emission scenarios, while the range estimated with RCM-based scenarios was 4 to 8.5 weeks (up to 7 RCMs with two driving GCMs and A2 and B2 emissions).

Future changes in modelled inter-annual climate variability are seldom investigated in impact studies, due to climate model bias (see above). However, by devising a method of superimposing modelled inter-annual variability onto (unbiased) observed mean climate, this effect could be investigated in relation to grain maize suitability. Projected higher temperature variability was estimated to reduce the zone of reliability for grain maize ripening at the fu-

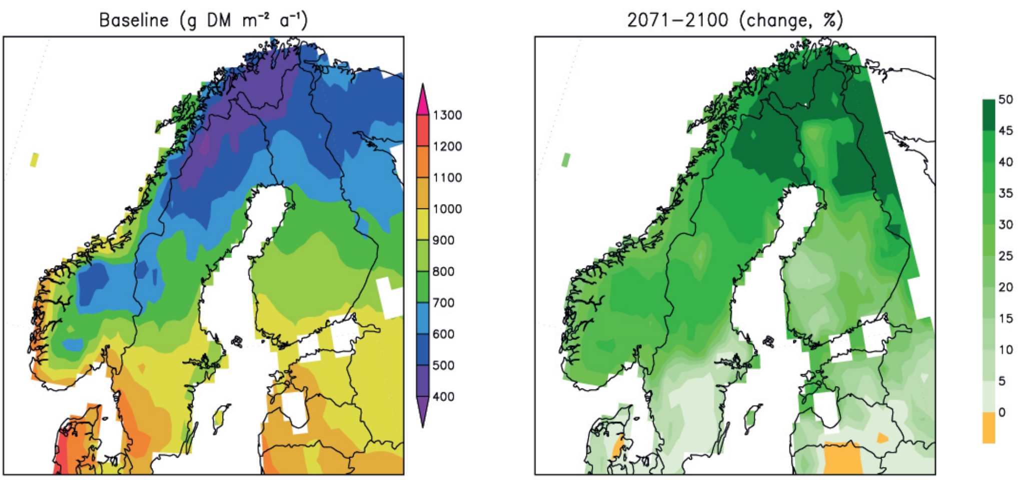

Figure 6: Net primary productivity computed using Lieth's (1975) empirical relationship a) for observed baseline climate 1961–1990 (g DM m^{-2} a^{-1}) and b) simulated changes of a 6-RCM-ensemble-average (SRES A2) for 2071-2100 relative to 1961-1990 (%). The Lieth model does not account for the fertilizing effect of increased atmospheric CO_2 concentrations.

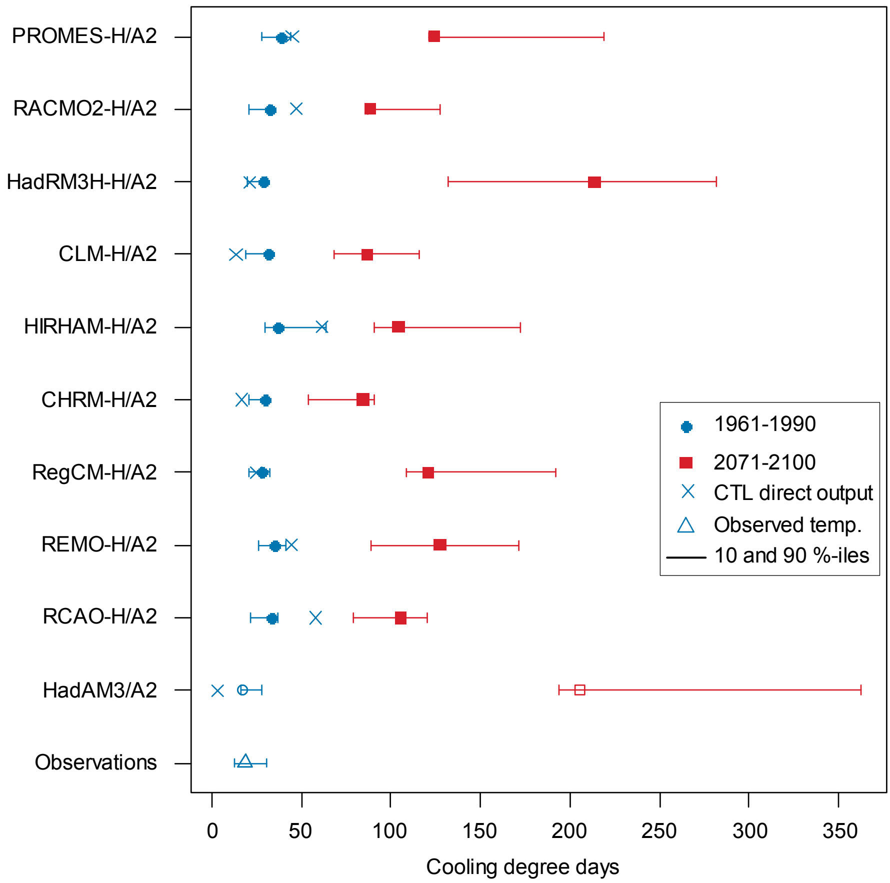

Figure 7: Cooling degree days above 18°C for the Helsinki grid cell for the baseline 1961-1990 (blue) and future 2071-2100 (red) periods. Blue symbols are estimates of means assuming 1961-1990 observed mean temperature and inter-annual variability (IAV, triangle) and observed mean temperature and modelled IAV (circles). Crosses show estimates based on modelled 1961-1990 temperatures. Red symbols are based on model projections (squares) for 2071-2100. Models are the driving HadAMH/A2 simulation (open symbols) and nine RCMs nested within in (solid symbols). Error bars show 10 and 90 percentiles of the 30-year estimates. This figure is a more detailed close-up for the Helsinki grid cell of Figure 6 in paper **III**.

ture northern limit of suitability in central and northern Finland compared to the limit with unchanged variability (Figure 3 in paper **III**). Aspects of variability change were also investigated in relation to energy demand for cooling in some European cities (paper **III**). The demand at Helsinki was estimated to increase by 3 to 7 times based on RCM-based climate projections from a relatively low level during the baseline period 1961-1990 (Figure 7), although the demand would still remain below present-day levels of central European locations.

3.3 Modelling the impact of climate change on palsa distributions

3.3.1 "Conventional" scenario analysis

The majority of palsa models developed in this study showed a consistent sensitivity to changes in temperature and precipitation with increases (decreases) in either of them resulting in decreases (increases) in the area suitable for palsas (Figure 5 in paper **II**, Table 4 in paper **V**). It was estimated that all baseline palsa areas become unsuitable with a warming of more than 4°C, whereas some suitable areas still remain even for increases in precipitation of up to 30% (Figure 5 in paper **II**). The sensitivity of palsa models to joint changes in temperature and precipitation was also depicted in impact response surfaces (Figure 8; Figure 5 in paper **IV**, Figure 4 in paper **V**). Projections for the period 2010-2039 with seven GCM-based scenarios and SRES A2 forcing show the palsa area that becomes unsuitable along the edges of the current distribution, with the largest area losses in the north-eastern part north of Lake Inari in northern Finland (Figure 9). The area with the largest number of scenarios projecting remaining palsa suitability in the near-future period, 2010-2039, lies in northernmost Sweden north-west of Kiruna. Further decreases of suitable areas with similar spatial patterns were projected for later periods with all but one scenario for 2070-2099 projecting the total loss of suitable palsa areas. (Figures 6 and 7 in paper **II**).

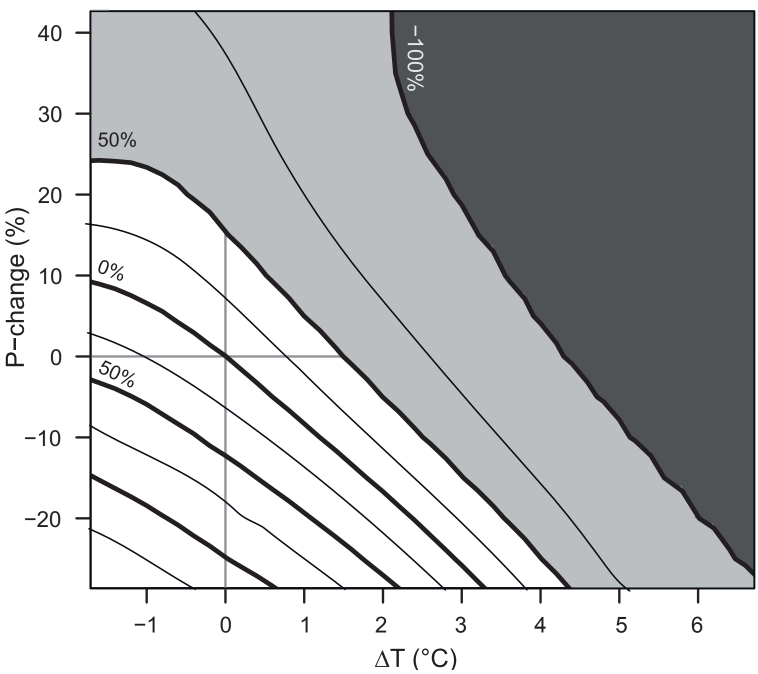

Figure 8: Impact response surface showing the change in area suitable for palsa mires (contours in 25% steps from 50% to -100%) for a 25-member ensemble mean of GAM palsa models. Temperature- and precipitation change combination for which the total loss of area suitable for palsa is estimated in shown in dark grey, those that result in at least 50% area reduction in light grey.

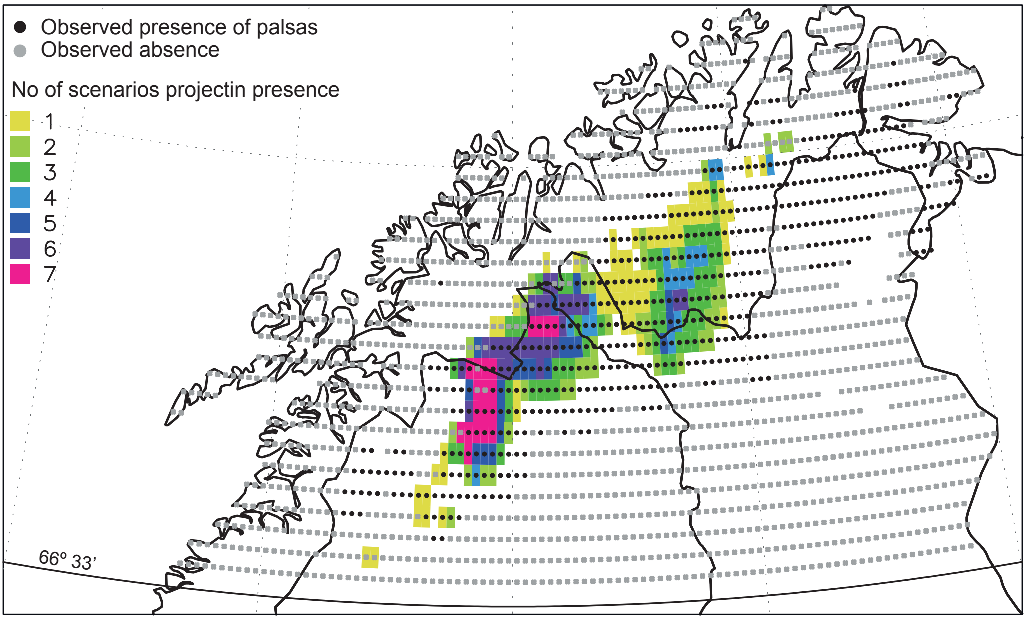

Figure 9: Observed palsa presence/absence and number of GCMs for which palsa presence is projected for the period 2010-2039 for an ensemble of 7 GCM simulations with SRES A2 forcing using the GAM palsa model of paper **II**.

3.3.2 Application of probabilistic climate projections and assessment of uncertainties

Probabilistic projections of climate change were superimposed on impact response surfaces to estimate a distribution of future impacts (Figure 6 in paper **IV** and Figure 5 in paper **V**). A comparison of these results to estimates achieved with a "conventional" scenario analysis, but using the same probabilistic climate change projections, showed that the impact response surface approach gives a very similar distribution of impact estimates (Figure 7 in paper **IV**). The probability that all palsa areas become unsuitable was estimated to increase during the 21st century from estimates of 0% for the earliest periods (1991-2020 in paper **IV**, 2000-2019 in paper **V**) to a range of 43% (B1 scenario) to 100% (A2 scenario) at the end of the century (Figure 10). Impact estimates for an ensembles of GCM simulations forced with the E1 mitigation scenario showed a reduced risk of palsa loss by the end of the century compared to A1B forcing, with 7 out of 11 ensembles members resulting in at least some remaining palsa area, whereas all areas become unsuitable for all ensemble members of the corresponding simulations with A1B forcing (Figure 5 in paper **V**).

Impact response surfaces constructed for an ensemble of palsa models showed that the choice of the statistical modelling technique affects the range of estimated changes in palsa suitability for changed climatic conditions. While estimates of the parameter uncertainty of GAM palsa models were smallest, ensembles of palsa models constructed with other modelling techniques resulted in a much wider range of impact estimates, with some impact response surfaces not showing decreasing palsa suitability with warming and some palsa areas remaining suitable even for very large temperature increases (Figure 4 and Table 4 in paper **V**). Estimated probabilities of all palsa areas becoming unsuitable by the end of the 21st century range between 0% and 84% across all palsa models, whereas the range of estimates was reduced to 35-84% if only models fulfilling two criteria of model plausibility were considered (Figure 6 in paper **V**).

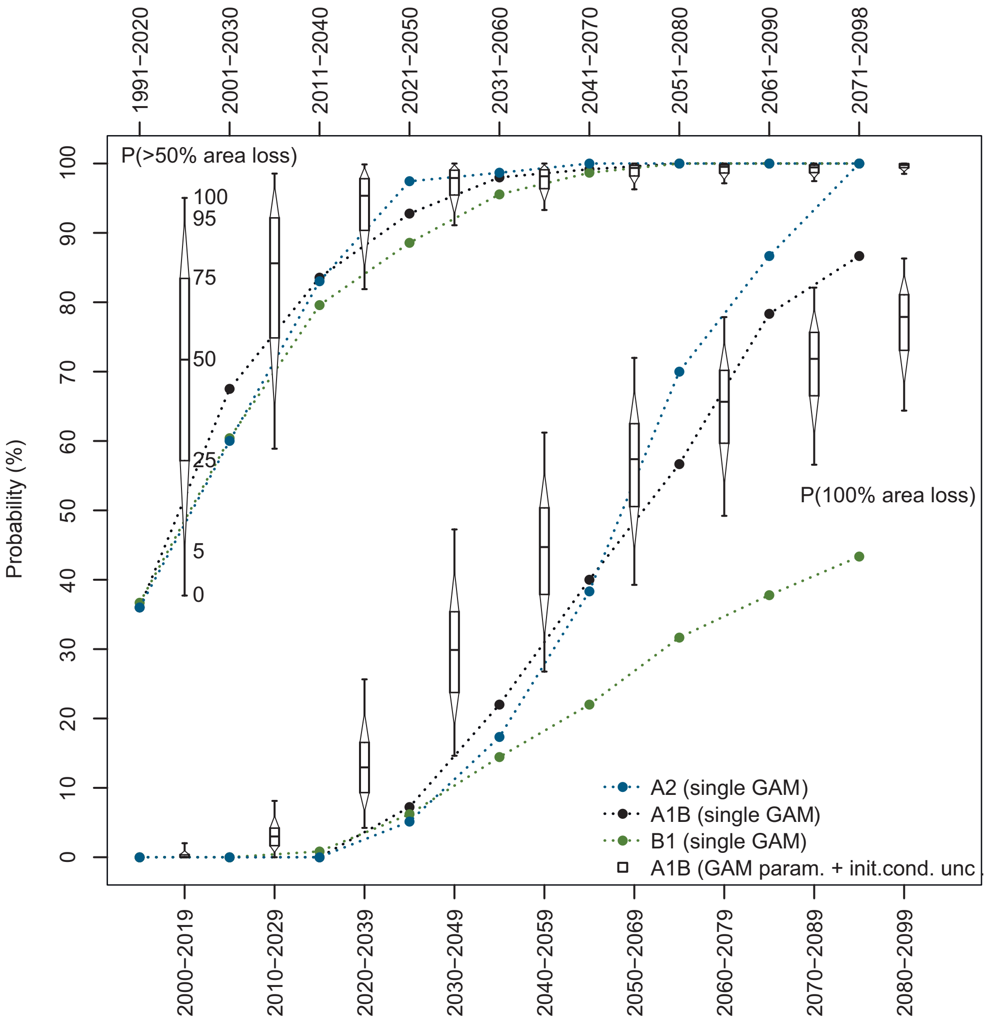

Figure 10: Probability of half (lines and boxplots at the top) and all (bottom) palsa areas becoming unsuitable estimated with the impact response surface approach using a resampled 15-GCM ensemble for a single palsa GAM model (lines, based on Paper **IV**) and the confidence intervals for an ensemble of palsa models combining parameter uncertainty for GAM and initial conditions uncertainty (boxplots, based on paper **V**).

4 Discussion

The climatic envelope models of northern Fennoscandian palsa mire suitability presented in this study were capable of reproducing the observed distribution of palsas and achieved excellent evaluation statistics based on climate variables alone. Uncertainty in these models was quantified by calibrating an ensemble of 600 palsa models, which is a much larger sample size than commonly applied in envelope modelling studies of a single distribution dataset (Heikkinen *et al.* 2006, Jeschke and Strayer 2008, but see Buisson *et al.* 2010 for an exception). The ensemble of palsa models showed a considerable variation in outcomes when extrapolating across a range of climatic conditions, as revealed when plotting model behaviour as impact response surfaces. Some of the models failed to fulfil two criteria of plausibility that were defined using the impact response surfaces: they did not predict decreases in palsa suitability with warming or they predicted some remaining palsa areas even for large amounts of warming. This was in spite of their general good performance in commonly applied evaluation statistics that measure a model's ability to reproduce the observed spatial distribution, suggesting that these test statistics alone may not be sufficient to judge if a model can be applied with changed climatic conditions.

Even considering the rigorous attempts made to assess the uncertainty of palsa envelope models, some factors were not accounted for that have been recognized as important for the presence of palsas. These include a sufficiently thin snow cover (Seppälä 1982) and non-climatic information such as the presence or absence of a peat layer. Proxies of these can become more important for analysis conducted at a finer scale than the grid cell size of *c*. 120 km^2 used in the present study. Finer-scale analysis of palsa distributions has been carried out in Finnish Lapland with topographical and land cover variables calculated for 1 km^2 (Luoto and Seppälä 2003) and with topographical and soil variables for 0.25 km^2 grid cells (Hjort *et al.* 2007). Bosiö *et al.* (2012) have applied high resolution (30 arcseconds cell spacing corresponding to a cell size of approx. 1 km^2) interpolated climate data to estimate climate suitability for palsas at a set of study sites in northern Fennoscandia, based on threshold values presented in paper **I** of this study. They related the hummock vegetation types observed at the sites to these suitability measures and then projected this relationship to a wider region similar to that used in this study, using information derived from a land cover map at 1 ha resolution. An example for the effect of grid cell resolution on the outcome of climate envelope models has been presented for mountain plant species distributions by Trivedi *et al.* (2008). They found that finer scale analysis (5 x 5 km^2 resolution) resulted in stronger shifts of species ranges than coarser scale analysis (50 x 50 km^2 resolution). Inaccuracy of the response variable, the presence or absence of palsas within each study grid cell, is another potential source of error that has not directly been addressed in the analysis. The source information of the palsa distribution map could be incomplete or errors in transcribing the information to the gridded map could have occurred.

Projections of the future distribution of palsa mires have been made using climate projections constructed from the output of climate model simulations. These quantify uncertainties in emissions scenarios (inter-scenario variability) and the response of different climate models to these scenarios (inter-model variability) using both conventional ensembles of GCMs and probabilistic projections. A single scenario construction method, the delta-change approach, was applied, although some climate indicators have also been calculated directly with dynamically downscaled projections. The choice of a simple scenario construction method was motivated by the low data requirements of climate envelope models. These typically require only long-term averages of relatively simple climate indicators; transient information about how these evolve over time, including possible changes in variability, cannot directly be processed by these types of static impact models. The choice of an appropriate downscaling method is more complicated for impact models that require climate variables at daily or sub-daily time-steps, or where climate variability change is a focus of analysis.

The palsa climate envelope models assume the palsa distribution to be in equilibrium with current long-term climatic conditions. They do not contain information about the variability of climate over short time-scales, although it is known that degradation of palsas can take place within a few years (Luoto and Seppälä 2003). A possible increase in the inter-annual variability of temperature, as has been demonstrated here for RCM simulations using a temperature-based indicator, could therefore also imply a faster decay of palsas, as years with climate diverging strongly from the long-term mean would be more frequent.

This study also demonstrated how an impact modelling approach could be extended, by constructing impact response surfaces, so that probabilistic projections of climate change can be applied directly to estimate the likelihood of future impacts. Examples of surfaces that plot an impact variable as a function of changes in two climate variables have been presented in the literature for more than two decades (Yoshino *et al.* 1988, p. 819, Rosenzweig *et al.* 1996). Jones (2000) suggested to combine such surfaces with probabilistic projections of climate change to estimate the risk of exceeding impact thresholds. This study builds on his idea, but uses more comprehensive projections of climate change than were available at the time when Jones' analysis was conducted, compares results achieved using impact response surfaces with those achieved using more conventional scenario analysis (see paper **IV**) and expands the approach by dealing with seasonally scaled temperature changes. Impact response surfaces present impact model results with respect to changes in just two climate variables, hence requiring a simplification of most impact models. Here, the palsa models require monthly temperature data, whereas the impact response surfaces are plotted against changes in annual temperature. Despite this simplification, the comparison of results to conventional scenario analysis showed only relatively small differences. Constructing reduced-form impact models from more complex models than the palsa example, that require more climate variables than temperature and precipitation in smaller time steps, would also require more assumptions about how the climate input data is related to the two variables against which impacts are plotted; this could increase the error introduced by using the impact response surfaces.

Impact response surfaces have a number of potential uses and advantages which are schematically illustrated in Figure 11 for a hypothetical example of crop yields (used here to illustrate aspects that do not all apply to the palsa example). Response surfaces allow critical impact thresholds to be plotted for climate changes relative to a reference climate and can help to identify impact discontinuities if these exist (Figure 11A). Uncertainties of impact models can also be displayed by comparing different response surfaces on the same plot (Figure 11B, see also Figure 4 in paper **V**). Another advantage is that response surfaces can help to identify climate conditions to which a system is vulnerable, independent of a specific climate change scenario, and enable or aid in a "bottom-up" impact assessment in which climatic conditions critical for a certain impact to occur are identified before giving concrete projections for the future using climate scenarios (Brown et al. 2011, Weaver et al. 2013). This allows to identify changes in impact behaviour following adaptation, for example the switch to a different crop variety better suited for warmer conditions, which can be plotted to evaluate advantages gained by adaptation (Figure 11C).

Impact response surfaces, by definition, provide estimates of impacts across a wide range of climatic conditions. An impact estimate can therefore be read off from the surface for any new climate change projection expressed using the same variables, without having to run the impact model again (Figure 11D). Such a "scenario-neutral" approach (Prudhomme *et al.* 2010) simplifies the evaluation of large climate change ensembles, such as the probabilistic ones used in this study, and allows a rapid assessment of climate change projections for many time-slices and scenarios. Applying probabilistic projections of climate change with the palsa response surfaces also provides an opportunity to estimate the likelihood or risk of palsa loss (cf. Figure 10), in contrast to a conventional impact assessment that produces only a range of possible impacts that are dependent on the set of climate scenarios selected.

The projected decline in northern Fennoscandian palsa mires will directly affect vegetation by modifying hydrological conditions, often resulting in wetter conditions (Malmer *et al.* 2005), and nutrient availability to plants (Keuper *et al.* 2012). In combination with the effects of increased temperatures and CO_2 concentrations in the air, this can increase plant productivity and modify the species composition. Bosiö *et al.* (2012) project that dry hummock vegetation typical for palsas in the study area will increasingly be replaced by wet hummock vegetation. This is also in line with projected vegetation changes in simulations

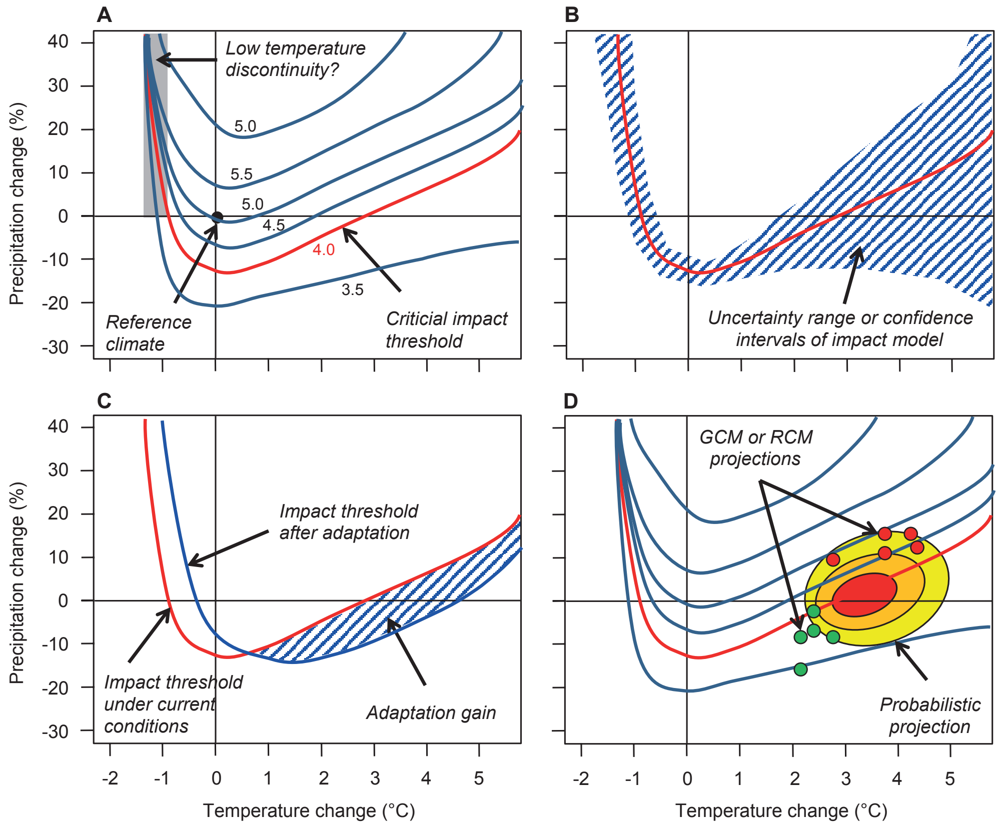

Fig. 11: Schematic impact response surfaces (IRSs) of a hypothetical impact model illustrating key features and some of potential uses. IRSs depict impact behaviour across a wide range of climate changes relative to a reference climate, so that: critical impact thresholds can be plotted and possible impact discontinuities identified (A); impact model uncertainties can be displayed (B); changes in impact behaviour following adaptation can be plotted to evaluate advantages gained by adaptation (C); and different climate change projections can be overlaid to allow a rapid assessment of impacts or of impact risks where probabilistic projections are applied (D). The IRSs shown could be for average crop yields (in t/ha) and a possible adaptation option (C) could be the switch to a different crop variety. The colour shading of the probabilistic projection in D illustrates the probability distribution with red indicating higher probability than yellow.

with a dynamic vegetation model that indicate shifts from one vegetation type to another in large parts of northern Fennoscandia (Hickler *et al.* 2012). Effects on the regional carbon balance of palsa mires depend on local conditions (e.g. Hugelius *et al.* 2011), and the answer to the question if a palsa mire becomes significant sink or source of carbon remain uncertain (Bosiö *et al.* 2012, Olefeldt *et al.* 2012). Changes in the mire hydrology and vegetation can also reduce the habitat availability for bird species that have palsa mires as one of their preferred nesting habitats. Reductions in bird population have been observed for mire- and wetland-loving species of the north over recent decades (Virkkala and Rajasärkkä 2012) and these reductions are projected to continue into the future (Virkkala *et al.* 2008).

5 Conclusions

This study has offered an assessment of several sources of uncertainty in climate change impact assessment, using the case study of subarctic palsa mires. The main conclusions to be drawn from the results of this work are as follows, grouped by the three themes of the thesis:

Modelling the effects of climate on the distribution of palsas and associated uncertainties

1. The present-day spatial distribution of palsa mires in northern Fennoscandia can be largely explained by climatological variables alone.
2. Palsa mires are sensitive to changes in climate. Increasing temperature and precipitation will decrease the extent of the palsa distribution.
3. Metrics of climate envelope model performance that are commonly applied are not sufficient to evaluate the performance of model extrapolations with climate change scenarios. Impact response surfaces can help to evaluate models; this was demonstrated by defining two additional plausibility criteria that related to knowledge of the processes being modelled. It is recommended that such procedures be followed *prior* to an impact model's application with climate scenarios. Applying these plausibility criteria with an ensemble of palsa models demonstrated that structural differences appeared to be a major source of impact model uncertainty.

Representing future climate in impact studies

4. The results of climate change impact analysis can be strongly influenced by the methods of constructing projections of future climate. This study compared a simple delta change approach with several ensembles of GCM simulations with dynamically downscaled projections. The possible additional value of RCM-based compared to GCM-based scenarios depends on the impact study. Although RCM projections are dependent upon the GCMs they were nested within, systematic differences between RCMs and their driving GCM were detected for many regions in Europe. However, RCM-based scenarios alone are unlikely to embrace a representative range of possible future climate as long as ensembles are available only for a limited number of driving GCMs.
5. Probabilistic projections of climate change offer the opportunity to express future impacts in terms of risk, but they also present a substantial computational challenge to impact modellers. The impact response surface approach demonstrated in this study can considerably reduce the number of impact model simulations required for a probabilistic assessment; especially when climate projections for many scenarios and time periods are being analysed.

Projecting impacts of future climate change on palsa distributions

6. Projections with climate scenarios implied a considerable loss of palsas already in the early decades of the 21st century and a high risk of total palsa loss by the end of the century. The risk of more than half the current palsa areas becoming unsuitable was quantified as *very likely* (>90% probability) for periods from 2030-2049 onwards and the risk of all areas becoming unsuitable as *likely* (>66% probability, 90% confidence) by 2080-2099 for the moderate A1B emission scenario. The risk was higher for the high A2 emission scenario and reduced for the lower B1 emission and the E1 mitigation scenarios, although these too implied a considerable reduction in palsa areas.
7. An increase in mean annual temperature of more than 4°C relative to 1961-1990 was estimated to result in the loss of all palsas in northern Fennoscandia. This was projected to occur with a smaller amount of warming, if precipitation increases at the same time.

Future work on the topics of this thesis could include an application of the presented palsa models to areas outside northern Fennoscandia. An extrapolation of the models to the northern hemisphere would be relatively easy to implement with existing global climate databases. To be able to validate such extrapolations, it would be useful to gather more detailed information on the observed distributions of palsas in North America and Russia. Another possible use of the palsa models would be to apply them with paleoclimatic conditions from cooler periods of the Holocene and compare the predicted palsa suitability with presumed relict palsa formations in central Europe and elsewhere (Gurney 2000, Pissart 2002).

The impact response surface approach presented in this thesis has been used to evaluate the plausibility of impact model extrapolations and to combine impact estimates with probabilistic projections of climate change to quantify impact risks. This approach could potentially be applied in a wide range of model-based climate change impact studies. It would be interesting to develop other case studies with climate envelope models of species or habitat distributions to try to define similar criteria of model plausibility to those presented here for the palsa models. Such criteria could be based, for example, on species traits. Climate envelope models are mostly being evaluated purely on the basis of evaluation statistics, such as AUC and Kappa, which compare model projections to observations, the latter usually not being truly independent from the observations used for model calibration. As was demonstrated in this thesis, model extrapolation may nevertheless be unreliable despite showing good values in evaluation statistics. Impact response surfaces can help to conduct more rigorous tests of model behaviour, hence making impact estimates more reliable.

The approach can also be used with more complex impact models that require daily input data and other climate variables than only temperature and precipitation. One of the challenges here is how the more complex input data can be mapped to a 2-dimensional space of climate variables that are used to span the impact response surface. Some examples have already been developed with dynamic crop (Ferrise *et al.* 2011, Børgesen and Olesen 2011) and hydrological (Prudhomme *et al.* 2010, Weiß 2011, Wetterhall *et al.* 2011) models, in which early attempts to tackle these challenges are presented. A further step would then be to analyse, in addition, aspects of impact model uncertainty with more complex models (cf. Rötter *et al.* 2011). By using a less demanding modelling approach in terms of input data and computational power requirements, this study can serve as an example.

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